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Damage analysis of brick-to-mortar interfaces

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Abstract

A laboratory procedure aimed at generating a progressive deterioration of the interface between brick and mortar layers in controlled experimental conditions was developed at the Non Destructive Testing Laboratory of the Politecnico di Torino. It is intended as a preliminary stage in the design of a pre-qualification procedure to be applied to repair mortars for restoration of historical masonry buildings. Indeed, assessing the durability of repair products is a major concern because of the potential occurrence of de-bonding phenomena due to insufficient compatibility between original and repair materials, in terms of their mechanical characteristics. Therefore, the study of the long-term mechanical interaction between repair mortars and historical masonry substrate turns out to be crucial for the design of durable repair works.
In this direction the evolutionary phenomenon of mortar de-bonding generated in the lab is analyzed here through the cohesive crack model. The numerical simulation of the laboratory tests was shown to be able to describe the experimental evidence correctly, thus allowing us to characterize the mechanical behavior of the interface. It is therefore possible to use the analysis presented here to predict de-bonding phenomena in problems with different boundary conditions by changing the simulation parameters properly.

Keywords: brick, mortar, plaster, debonding, delamination, cohesive crack, fracture, damage,bi-material interface, fictitious crack;

1. Introduction

The laboratory procedure here described was defined in order to create a progressive deterioration at the interface between brick and mortar in a bi-material system, in such a way to simulate a realistic de-bonding phenomenon in an accelerated time frame. It consists in the application of static loads to mixed brick-mortar specimens having peculiar characteristics in terms of geometry and adhesion at the interface (as described in Section 2), with continuous monitoring of the longitudinal and transverse displacements.
A numerical simulation based on the cohesive crack model was used to follow the experimental data, so as to describe the evolutionary phenomenon of de-bonding as a function of a small number of parameters and identify potential precursors of the interface failure, that could be used in the future in the framework of a prequalification

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procedure aimed at characterizing the long-term compatibility between restoration materials and original historical materials.

2. Materials and specimens

The geometry of the specimens is shown in Fig. 1. The external layers of repair mortar were not applied in complete adhesion to the brick support, on the contrary they were applied in symmetrical and regular discontinuity, created in the casting phase through the interposition of a thin steel leaf. These discontinuities, shown in Fig. 1, behave as notches which are able to trigger multiple crack propagations. The mortar was prepared by mixing cement, sand and water in proportions 1:3:0.5. Specimens were instrumented with seven transducers and tested 28 days after the cast. The mean value of the mortar compressive strength, evaluated after de-bonding test, was 36.8 N/mm^2 and the mean value of the Young's modulus was 19500 N/mm^2. The elastic properties of brick and mortar are reported in Table 2.

3. Experimental setup

The static compressive tests were performed with the aid of a 250 kN MTS operating in displacement control. The velocity of the machine piston was 0.001 mm/s. Two teflon leaves, 1 mm thick, were located below the specimen in order to reduce friction related to the horizontal expansion. The experimental setup is shown in Fig. 2.

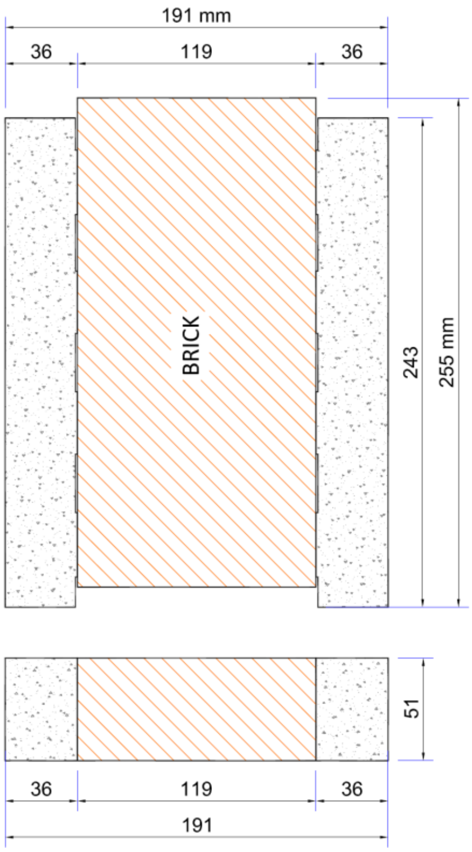

Fig. 1. Geometry of specimen.

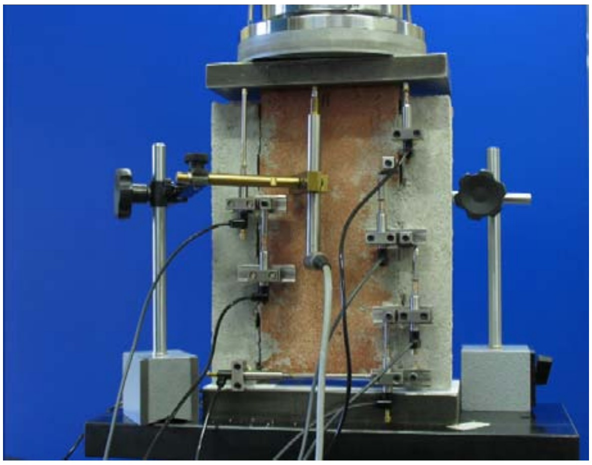

Fig. 2. Experimental setup.

4. Numerical simulation through the cohesive crack model

The most realistic method used today for the numerical simulation of mortar and brick fracture is the cohesive crack model, introduced by Barenblatt [1] and Dugdale [2] for elasto-plastic materials and by Hillerborg *et all* [3] for quasi-brittle materials. In the present work the crack initiation criterion is assumed as:

$$\left(\frac{\sigma_0}{f_t}\right)^2 + \left(\frac{\tau_0}{f_s}\right)^2 = 1 \qquad (1)$$

where σ_0 and τ_0 are stresses evaluated along the directions normal and tangential to the interface and f_t and f_s are the related strength. The point where equation *(1)* is satisfied is called *fictitious crack tip*.
According to this method the cohesive stresses acting on the non-linear fracture process zone (shortened FPZ) are decreasing functions of the effective value of the displacement discontinuity (see [4],[5],[6]). In the present work it was assumed:

$$w_{eff} = \sqrt{\left(\frac{w_n}{w_{nc}}\right)^2 + \left(\frac{w_t}{w_{tc}}\right)^2} \qquad (2)$$

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where w_n is the mutual displacement component normal to the interface and w_t the tangential one. w_{nc} e w_{tc} are the related critical values.
If $w_{eff} > 1$ no stress transfer occurs and therefore the crack is stress free. Otherwise the stresses are decreasing functions of w_{eff} following a pre-defined softening law. In the present work the above mentioned law is linear, starting from σ_0 and τ_0 and ending in the point where $w_{eff} = 1$ called *real crack tip*. The behavior of the material outside the FPZ is linear elastic.
In a symmetric model, it is well known (see [7]) that the fracture process starts symmetrically, but loses this property before the peak load is reached. In order to simulate numerically this experimental evidence, a realistic scatter in strength was assumed, as shown in Table 1.

Table 1. Interface parameters

	f_t N/mm^2	f_s N/mm^2	w_{nc} mm	w_{tc} mm
left side	1.5	1.5	0.01	0.01
right side	1.3	1.3	0.01	0.01

Therefore the collapse is determined by a de-bonding process occurring on the right (weaker) side.
Table 2 shows the elastic properties assumed.

Table 2. Elastic properties

	Young's module N/mm^2	Poisson ratio -
Mortar	19500	0.15
Brick	14500	0.20

The numerical analysis were executed through the code ABAQUS [8] by applying a pre-defined downward velocity to the upper face of the brick. The deformed finite element mesh shown in Fig.3 is related to the last Newton-Raphson equilibrium iteration.

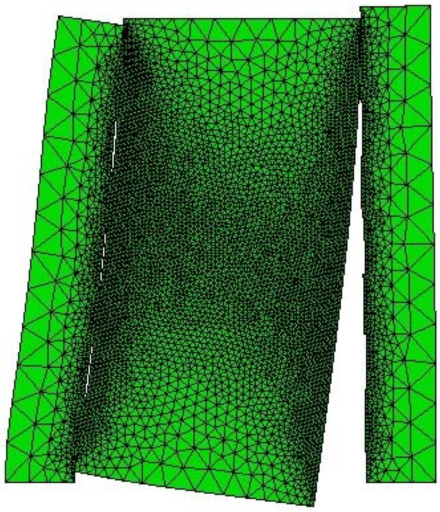

Fig. 3. Finite element mesh at the end of the fracture process.
Displacements are enlarged 781 times.

5. Experimental and numerical results

In Fig. 4,5 and 6 the ordinates are divided by the maximum values, shown in Table 3.

Table 3. Maximum values of load and displacement.

	Load max	Loading point max vertical displacement	Mortar –to-mortar max horizontal displacement
	N	mm	mm
specimen 1	8655	0.32	1.60
specimen 2	5809	0.37	1.14
num. simulation	7497	0.019	0.042

Time values are normalized by assuming the value T=1000 s at peak load. Table 3 shows that the maximum value of displacements, evaluated experimentally, is always larger than the same value, obtained numerically. The numerical analysis have to be arrested as soon as uniqueness of incremental solution is lost in the model. On the contrary the experimental test can be executed up the complete plaster de-bonding. With reference to the vertical displacement, it's worthwhile noting that experimental values include the deformation of the teflon leaves. On the contrary, in the numerical simulation, this contribution is neglected.
All diagrams start when the external load exceeds 10% of the maximum value. The vertical displacement achieved at this time was assumed as zero.
In this way the effects of local settlements occurring at the supports are reduced on the experimental diagrams. The numerical diagrams are not sensible to local support settlements and therefore starts linearly from the origin.

In Fig. 4 and 5 symbol (□) indicates the global horizontal displacement evaluated from the mortar on the left side to the mortar on the right. In both cases this diagram shows a knee point: on the left there are small values due to elastic deformation, on the right large values due to the non-linear fracture process. The above mentioned knee point occurs at the time of the peak-load. It means that the crack growing from the bottom to the top causes the global softening branch. Fig. 6 shows the same diagrams obtained through the cohesive crack model. Numerical and experimental results are in good agreement.

In Fig. 4,5 and 6 symbol (△) indicates the vertical displacement of the loading point. Since this is the control parameter, the numerical response is perfectly linear. From the experimental point of view, a constant velocity of the machine piston was enforced. Therefore small deviations from the linear diagram are due to the elastic global behavior of the testing machine.

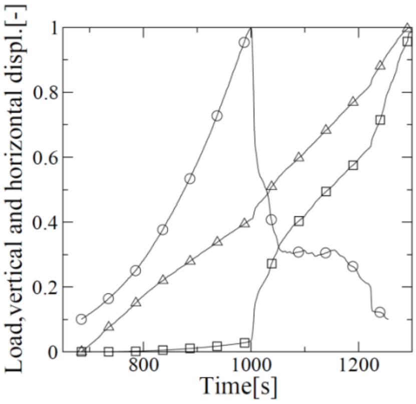

Fig. 4. Dimensionless experimental results for the first specimen: (○) load, (△) loading point vertical displacement, (□) mortar to mortar horizontal displacement at specimen bottom;

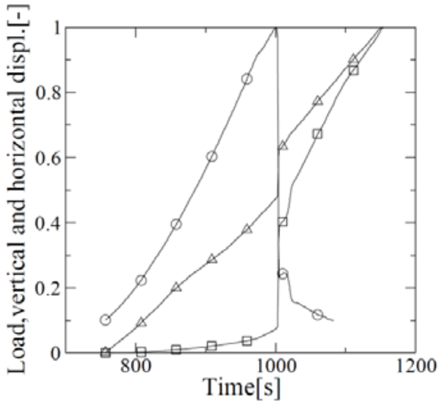

Fig. 5. Dimensionless experimental results for the second specimen: (○) load, (△) loading point vertical displacement, (□) mortar to mortar horizontal displacement at specimen bottom;

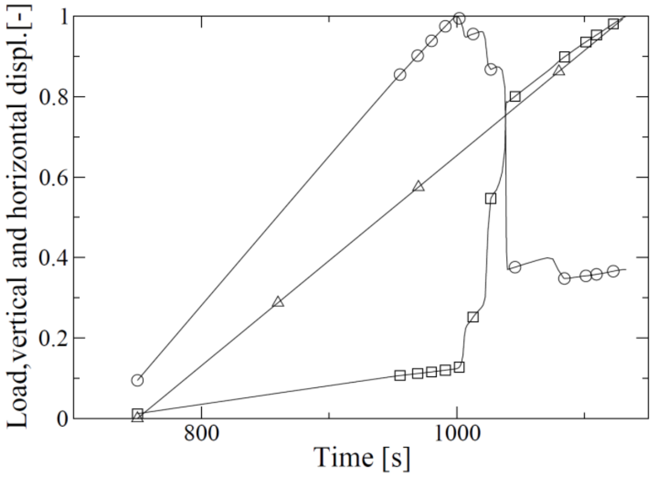

Fig. 6. Dimensionless numerical results: (○) load, (△) loading point vertical displacement, (□) mortar to mortar horizontal displacement at specimen bottom;

6. Conclusions

- The evolutionary phenomena involved in the de-bonding process of mortar in a coupled brick-mortar system are accurately analyzed by means of the experimental setup proposed.
- Through the cohesive crack model it was possible to interpret theoretically the above mentioned phenomena occurring at the interface between brick and mortar.
- Therefore the mechanical behavior of the interface is characterized. The parameters obtained can be used for the analysis of a problem with different boundary conditions.

Acknowledgements

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